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Aircraft Systems Report 40

THERMAL STRESS IN RAN SEA KING HELICOPTER OPERATIONS (U)

by

J.G. Manton & K.C. Hendy*

Approved for Public Release

* Now at the Human Engineering Section, Defence and Civil Institute of Environmental Medicine, Downsview, Ontario, Canada.

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SUMMARY

This Report deals with thermal stress in aircrew operating in the cabin and cockpit environment of the RAN's Sea King helicopter. The high thermal loads experienced in the helicopter have previously been established and various options for ameliorating the conditions have also been proposed. A review of the literature on thermal stress research is presented. The development of an Index of Thermal Stress for the Sea King (SKITS) is reported along with the results of a study to determine the ameliorating effect of blown cooled air directed at the faces of subjects in a thermal chamber.

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1.. INTRODUCTION

Since the introduction of the Sea King Mk. 50 helicopter into service with the Royal Australian Navy (RAN), aircrew operating the aircraft have experienced excessive cabin temperatures on many occasions. This has caused the curtailment of operations and reduced the effectiveness of crew training in high ambient temperatures (Rebbechi, 1980). Data gathered in a Royal Air Force Sea King helicopter indicated that a two-hour sortie on a 27 degree C (dry bulb) day caused dehydration sufficient to cause degradation in the physical work capacity of the winchman wearing the Mark 2 immersion coverall (Gibson, Higgenbottam, Graveney and Redman, 1981). The two pilots on the same sortie, wearing flying suits, experienced significant dehydration and showed elevated body temperatures.

There are several ways in which the thermal strain experienced by aircrew in routine Sea King operations could be controlled, for example:

a. control the cabin environment such that aircrew thermal strain is contained under all ambient operating conditions;

b. provide aircrew microclimate conditioning via air-cooled or liquid-cooled garmets;

c. improve the local environment around the aircrew by reducing the radiant heat load, increasing the evaporative heat loss and providing a cool-air source (at least at face level) at each crew station; and

d. provide commanders with information which will indicate the degree of risk associated with flying operations conducted under varying degrees of environmental stress, so that flying in high risk conditions can be curtailed or avoided.

The best option for providing complete protection against thermally imposed strain is to condition the cabin air so that all physiological parameters (eg skin temperature, core temperature, sweat rate, heart rate etc) are maintained at 'thermally neutral' values, but this option may be prohibitively expensive. Microclimate conditioning has been shown consistently to be an efficient and cost effective alternative for maintaining the human physiological state within acceptable bounds. These options (a and b) are intended to achieve a virtually complete physiological solution, but the remaining options (c and d) are attempts to ameliorate the thermal strain experienced by the aircrew by preventing the physiological parameters from exceeding recognised safe limits.

Although the feasibility of conditioning the Sea King cabin was demonstrated (Rebecchi, op cit) it was the cost of procuring a suitable system, offset against the remaining life of type of the aircraft, which caused this proposal to be cancelled in September 1982. However a recommendation to pursue alternative methods of keeping aircrew from overheating was made. One of the responses to the RAN's Request for Tender for airconditioning the Sea King included an alternative system of cooling by the use of Liquid Conditioned Garments (LCGs). LCGs have proven to be an effective and relatively inexpensive method of microclimate control in a number of trial installations; however, their introduction into routine operational flying has been delayed by continuing problems in engineering development (Hendy and Manton, 1985).

The present report covers the work conducted over a 12 months period on a task sponsored by the Direc of Naval Aircraft Engineering (DNAE) on 'Thermal Stress in Helicopter Operations'. The aims of the task were:

a. to examine the efficacy and acceptability of personal conditioning systems for Sea King aircrew, with particular emphasis on the use of direct cool air impingement and LCGs;

b. to examine the use of personal conditioning systems for reducing the contribution of thermal stress to aircrew fatigue;

c. to provide DNAE with human factors requirements of a personal conditioning system for the Sea King helicopter, in a form which is suitable for incorporation into a Navy Staff Target; and

d. to develop a method for the thermal assessment of aircraft crew environments.

The aim which covered examination of the LCG proposal was based on the availability of a prototype system which was being developed commercially for the Canadian Forces. Information obtained from the Canadian authorities (Air Standardisation Coordinating Committee, Working Party 61, Coordinating Member - personal communication) indicated that a flightworthy LCG would not be available within the timescale of this project. It was therefore decided to evaluate a more immediately available solution which was judged to be blown cooled-air.

The specific activities carried out under this task fell in three areas:

a. An integration check was conducted on the compatibility of the Canadian LCG vest and hood with aircrew clothing using both Royal Australian Air Force (RAAF) and RAN aircrew. This work has been reported separately (Hendy and Manton, 1985) and will not be described in this report.

b. A model was developed to predict the thermal conditions in the Sea King cockpit based on the ambient temperatures on the ground at the point of departure. This model was used to provide interim guidance on hot weather operations for the aircraft and to determine the temperature conditions to be used in the thermal chamber during an experimental investigation. In the development of this model, Hendy (1985) discussed a number of factors that should be incorporated into a method for the thermal assessment of aircraft environments.

c. An experiment was conducted in a thermal chamber to compare the effect of cooled blown air on physiological parameters, psychological mood and cognitive performance variables for one group of aircrew, against another group of aircrew who did not experience the cool air.

2. BACKGROUND CONCEPTS TO RESEARCH ON THERMAL STRESS

A critical aspect of any thermal environment is the magnitude of the thermal load and the extent to which this load can be accommodated by the body's

thermogregulatory system within the normal homeostatic range of 'stress responses'. If the thermal conditions cause a breakdown of the homeostatic state, as indicated by the inability of the physiological responses to maintain thermoregulation, then the body can be considered to be experiencing 'strain' (Weiner, 1982). Hyperthermia, or the condition of elevated body temperature, can be a consequence of exposure to hot environmental conditions. However, body temperatures can be elevated and stable, eg during exercise, with the related physiological thermoregulatory mechanisms maintaining equilibrium at the elevated core temperature. Depending on the severity of the thermal load, the physiological stress response relies on altered responses in a number of structures involved in thermoregulation. These changes have a cost in terms of energy mobilization and a redistribution of the relevant resources. The consequence is that the physiological system can cope well with stress for a period of time, as long as essential resources are replenished, otherwise a state of physiological strain can develop.

Although hyperthermia is regarded as an effect in the physiological domain, commonly there are assumptions that psychological variables such as mood and motivation, as well as cognitive performance, are affected also. The evidence to date on the relationship between physiological, psychological and human performance variables is equivocal (Grether, 1973; Hancock, 1981). Nevertheless the proposal being investigated here is essentially that exposure to an environment which causes a stress reponse, in which the length of exposure is a factor, may decrease the effectiveness and/or the availability of aircrew in anti-submarine warfare aircraft.

2.1 Temperature Measurement

Air temperature alone is not an accurate indicator of subjective warmth in the environment. The importance of wind, sunshine and humidity is readily appreciated and a thermal scale which combines these variables into a single index could have a great deal to recommend it. Several indices of thermal stress have been developed which are based on empirical data, invariably collected in restricted conditions, rather than on an analytical model based on known physical laws. The consequence is that these thermal indices need to be interpreted carefully, giving regard to the conditions under which they were developed. The Effective Temperature (ET) and the Wet Bulb Globe Temperature (WBGT) are two scales that have been used extensively in research on the effects of hot environments on physiological responses and human performance. These scales provide a common metric across studies through which results can be compared, although the applicability of these or similar scales in specific cases may be arguable.

The ET scale is derived from a nomogram which was based on the equivalence of the sensation of warmth that subjects had in a test environment with the sensation experienced in a controllable reference environment of still saturated air. The WBGT index was designed to be a simplified version of the ET index corrected for radiant heat load (Kerslake, 1972). WBGT was developed to predict the possibility of heat casualties in army training operations in an open air environment when subjects were wearing olive drab trousers and shirts. With its success in this area many other reseachers have used the WBGT scale in research on thermal stress in aircraft and other environments. A major difference between the two scales is that in the ET scale air movement is an explicit factor and radiant temperature is not (though a correction for radiant temperature is available) whereas in the WBGT scale radiant temperature is a factor and air movement is not.

The WBGT index can be calculated using a number of different formulae depending on the methods used in collecting the temperature data and the environment for which the index is intended. Two forms of WBGT calculation are used in this report, viz:

$$WBGT = 0.7Twbn + 0.2Tg + 0.1Tdb, \text{ and}$$

$$WBGT = 0.7Twbp + 0.3Tg, \text{ where}$$

a. Twbn is the naturally convected wet bulb temperature;

b. Twbp is the psychrometric wet bulb temperature;

c. Tg is the temperature of a black globe (assumed to be of 150 mm diameter); and

d. Tdb is the dry bulb temperature.

2.2 Physiological Responses to Heat

The correlations between measures of physiological strain and the WBGT scale are often poor (Kerslake, 1972; Hendy, 1985). Much of the failure of thermal stress indices to predict physiological reactions in humans, even over the range of temperatures for which they were developed, is that none of them take account of individual differences in thermal physiological reactivity (Kerslake, 1972). It is therefore important to relate the thermal environment experienced with an individual's parameters of physiological reaction. At present the choice of which physiological parameters to measure in order to develop a stress/strain prediction is based on an incomplete understanding of the human thermoregulatory mechanism.

The initial physiological reaction to heat is essentially a homeostatic response which attempts to keep the temperature in the core of the body (Tcor) stable. When the external temperature is higher than body temperature then the principal method of cooling is by the evaporation of sweat. As temperatures increase so does sweating. This is accompanied by dilation of the blood vessels in the periphery of the body, eg arms and legs, and in all areas close to the surface of the skin. The evaporation of the sweat lowers the surface skin temperature and the blood exchanges heat with the cooled skin. The increased blood flow to the periphery requires an increase in heart rate (Hr) and there is an associated increase in plasma volume. The point at which the homeostatic process can no longer maintain the Tcor at a stable level is dependent on, amongst other things, the amount of metabolic heat generated by physical work and the environmental conditions. When the ET reaches 25 0 to 27.0°C at high workloads the Tcor, often measured rectally (Tre) or in the auditory canal (Tac), starts to rise. At lower workloads Tcor starts to rise at about 30.0°C ET (Lind, 1964). The point at which Tcor starts to rise in response to the environmental load (ie at a constant physical workload), may be considered to indicate that physiological strain has begun.

The length of exposure to conditions where thermoregulation manages to keep Tcor stable, but elevated, is of critical interest to this study. Most indices of thermal stress are based on data collected from experiments which did not exceed four hours in duration (Lind, 1964). As many exercise ASW sorties are of longer duration, it is necessary to determine what the critical factors are in

longer exposures. As Lind suggests, the limiting factor determining the ability to tolerate the thermal conditions over time is the effect of dehydration. When sweat losses are high, drinking during the exposure cannot usually make good all of the fluid loss. Failure to replace water lost in sweat over a three to four hour period can lead to an upset in the body's thermal balance and thereby precipitate acute heat illness (Pitts, Johnston and Consolazio, 1944). As dehydration levels increase so the sweating rate decreases, and Tre increases (Sawka and Pandolf, 1985) in response to the reduced evaporative loss.

2.3 Biological Temperature

A measure of Tcor should be taken in the inner part of the body where the temperature is regulated at a stable level. However, the concept of a 'core' is a convenient simplification as the temperatures of the heart, lungs, abdominal organs and brain may vary differentially. The outer shell temperatures measured on the skin can be up to 20.0°C cooler than the Tcor. A large number of studies on the effects of environmental temperature on humans have used Tre to indicate Tcor. Benzinger (1969) was most emphatic about this being the wrong place to measure Tcor when he concluded that:

> 'It is now difficult to understand why for more than 100 years in physiology as well as clinical medicine central temperature was measured in a location that was known not to contain nervous centers nor thermoreceptor fields.' (page 680.)

Other sites which have been used are:

a. the esophagus, where a temperature probe is swallowed by the subject and is suspended in the esophagus adjacent to the heart;

b. sublingual, where temperature is measured just under the tongue;

c. the stomach or gut, where a temperature sensor and miniature radio transmitter are swallowed as a pill and the temperature coded signals are picked up by an externally mounted radio receiver; and

d. the ear canal, where a temperature probe is inserted along the external auditory meatus to some point close to the tympanic membrane (some researchers have placed the sensor such that it actually touches the tympanic membrane).

The suspension of a temperature probe in the esophagus requires fortitude by the subject and the temperature is known to be affected by respiration and swallowing (Cooper, Cranston and Snell, 1964). This site for temperature measurement poses problems for gathering data in the operational environment, eg piloting an aircraft. Sublingual temperature is affected when subjects open their mouths and again placement of a semi-permanent probe would not be practicable in the operational situation where subjects were required to use voice communications. Use of a temperature-sensitive radio pill has many advantages in that once swallowed there is no impediment to normal physical activity. However this site of measurement is again remote from any known nervous centres involved in physiological thermoregulation and the pill temperature may vary with position in the gastrointestinal tract under otherwise homeostatic conditions.

Benzinger (1969) advocated the use of tympanic membrane temperature after a number of failures to detect changes in Tre after changes had occurred in other aspects of the thermal response of human subjects. It was assumed by Benzinger that the blood in the internal carotid artery supplies the hypothalamus which together with temperature sensors in the skin plays a dominant role in the regulation of body temperature. Benzinger argued that due to the proximity of the tympanic membrane to the carotid artery the tympanic membrane temperature reflects internal cranial temperature as mediated by the cranial blood supply.

However, measurement of temperature directly at the tympanic membrane is both uncomfortable and potentially dangerous especially in an operational context. Cooper, Cranston and Snell (1964) demonstrated that temperature measured approximately 10 mm from the membrane was affected by the manipulation of the temperature of the blood in the carotid artery, thus raising the possibility of taking the measurement adjacent to, but clear of, the tympanic memberane. Cooper et al also determined that there was a temperature gradient along the walls of the external meatus and that changes in blood temperature in the carotid artery are reflected in a shift in the gradient. Morgan, Nunneley and Stribley (1981) noted the susceptibility of Tac measures to the influence of wind effects and ambient temperatures. They concluded, amongst other things, that insulation was required between the ear and the environment and that a protective helmet should be worn by aircrew. They also recommended that Tre should be measured as well as Tac.

2.4 Cognitive Performance

The evidence to date on the relationship between physiological, psychological and human performance variables during thermal stress conditions is not clear. However, Grether's (1973) review of a number of research papers indicated that there is a general trend of decreased performance at ambient temperatures above which the human body can no longer maintain homeostasis. More recently Hancock (1981) has indicated that mental performance is unaffected by heat stress until physiological collapse is imminent. It should be emphasised that the data used by Grether and Hancock have come from laboratory experiments where exposure times and temperature conditions have varied substantially from one study to another.

Nevertheless, attempts to integrate the experimental findings from a consistent but uncoordinated stream of research on the effects of heat on human performance continues. Perhaps the most constructive reviews are by Hancock (1982 and 1986). In the first review, Hancock concluded that as the response required of the subject performing a cognitive task becomes more complex, so there will be an earlier decrement in performance due to exposure to a heat load. Hancock presented this finding in terms of the increase in Tcor 'induced' by the thermal conditions in the experiments concerned. A 1.6°C rise in Tcor is reported as the 'physiological tolerance limit' (Taylor, 1948, as reported by Hancock, 1982) and Hancock proposed that tasks which require a relatively simple response, eg mental and cognitive skills, are unaffected by an increase in Tcor of up to 1.3°C. Performances on a tracking task are affected with rises in Tcor of 0.8°C and the most complex responses, considered to be in experiments where subjects had to deal with two tasks simultaneously, are affected with rises in Tcor of 0.2°C. Bateman (1980) conducted a study on the effects of hot ambient environments on tasks which ranged in cognitive complexity and which were performed in pairs simultaneously. Bateman determined that a 0.4°C increase in Tcor did not significantly impair performance, but a trend was evident for

performance to be degraded on the most complex task pairs when performed simultaneously. Hancock (1982) did not include Bateman's data in his review.

Ramsey and Morrissey (1978) also summarised a large number of experimental findings using a multiple regression model and concluded that reaction time measures of cognitive performance were affected by increases in ambient WBGT temperatures and length of exposure, although performance on tracking tasks, complex tasks and vigilance tasks tended to be degraded more by the ambient temperature level than by increasing exposure time. Ramsey and Morrissey's conclusion, based on a set of experimental results completely different from that used by Hancock (1982), offers a slightly different complexion to the state of knowledge. A more recent study of tracking performance by Beshir, El-Sabagh and El-Nawawi (1981) found that tracking error was greater when subjects experienced hotter environments, which is in line with Ramsey and Morrissey's conclusions, and that the length of exposure increased tracking error as well. This latter finding is more in line with Hancock's conclusions.

Hancock (1986) in the second review looked at some early work, conducted by N.H. Mackworth in the late 1940s up to the early 1950s, on the effects of a thermal load on subjects performing 'skilled' tasks and simulated watch-keeping. Hancock reiterated Mackworth's conclusions that a highly skilled subject's performance is less susceptible to performance decrement during exposure to hot conditions than is the performance of subjects who are less skilled. Mackworth also determined that there was an interaction of duration of exposure with skill level such that the less experienced subjects demonstrate a decrement in performance earlier than more experienced subjects. Hancock briefly evaluated the competing theoretical explanations for these findings and concluded that the 'arousal theory' proposition that skilled subjects will be less aroused by 'stress stimuli' and therefore should perform less well than relatively unskilled subjects, does not fit in with Mackworth's findings. He then offered the theoretical propositions of automatic and controlled processing which contend that skilled operators are able to perform tasks in an automated manner which requires little active information processing. Less skilled operators have to operate in a more controlled manner such that the skilled response is under active process control. The contention is that the skilled responses, being mediated by a process having automatic properties, are less susceptible to perturbations due to physiological strain and adverse conditions than less skilled and more actively mediated responses. This 'two process' theory has been developed over a number of years (Neumann, 1984) and is being invoked to explain experimental findings which are not adequately accounted for by arousal theory (Folkhard, 1983; Hockey and Hamilton, 1983).

The concept of skill is an important element within the human factors framework of research on man-machine system performance. The concepts outlined by Bartlett (1932) and Welford (1958) have proven difficult to research within the traditional laboratory experiment as skill is essentially learned within a 'real world' domain with all the inherent interactions of an open system. The techniques of operations research and verbal protocol analysis are perhaps more appropriate. Nevertheless, the effects of a hot environment on some form of skilled performance should be investigated in an experiment concerned with human responses to heat stress.

Research into the effect of diurnal variations in human performance has some relevance to the study of heat stress. Much of the interest in this topic relates to educationalists who were interested in the observation that certain types of learning occurred faster at particular times of the day (Folkard, 1983).

Body temperature normally varies by approximately 0.5°C during a 24 hour cycle, being lowest between 0400-0800 (local time) and rising to its highest value between 1400-2200. A study by Blake (1967) determined that over a range of laboratory-based cognitive tasks (simple reaction time, vigilance etc.) performance improved as sublingual temperature increased during the day. However it was also determined that a task which relied on short term memory (STM) showed the opposite trend. Folkard, Knauth, Monk and Rutenfranz (1976) confirmed this finding using a task which involved searching for a string of letters embedded on a page of randomly selected letters. They were also able to show that when the target string consisted of two letters, a low STM load, then search performance improved with body temperature, but when the target string consisted of six letters, a high STM load, then performance decreased with body temperature. The concept of STM and that of working memory as used by Card, Moran and Newell (1983) are very similar. Card et al included the structure of working memory in their model of a human processor and indicated that the working memory capacity is a major determinant of goal-oriented behaviour strategies. They also indicated that complex skilled tasks such as air traffic control place a high load on worki[ng] memory.

The reduction in the cap[...] to learn new material or skills due to higher body temperatures probably i[...]gnificant factor where aircrew training takes place in hot cockpits. Nunnele[...]d, Myhre and Stribley (1978) found that under a heat load where subjects could still thermoregulate there was a significant reduction in the rate of learning in tasks involving some higher mental functions. Curley and Hawkins (1983) found a decreased ability to acquire new chains of behavioural responses during a heat acclimatization regime. These findings indicate that measures of learning are important for research work in the area and the findings have some relevance not only to training but also to rapid learning requirements in operational environments, eg emergency or new tactical situations.

2.5 Physiological Variables

In order to make the extrapolation from a laboratory study to an aircraft environment, both the exposure times and the temperatures used in the study should be representative of the operational environment. Perhaps more importantly it is necessary to produce in the subjects in the experiment the sort of physiological reactions to the thermal conditions that are experienced in the aircraft during hot weather flying. If psychological factors such as motiviation and mood are a factor in cognitive performance then these should also be representative of the operational situation as well. However it is far more difficult to control these variables than the physiological responses being considered. Nevertheless, exposure to a hot environment, over a period of time which represents a sortie in an anti-submarine warfare helicopter, may result in performance effects due to fatigue factors. A satisfactory working definition of fatigue is

> 'a reduction in the capacity for performance as a result of working'. (Hartman, 1967.)

Cameron (1973) argued, amongst other things, that the only variable that is uniquely identifiable with fatigue is time. Fatigue is considered to be fundamentally a subjective feeling (Singleton, 1978), and when measured the construct is usually presented in terms of 'energy' (Bartley and Chute, 1947).

A study of pilot performance in a helicopter simulator by Stave (1977) determined that performance was not related to feelings of fatigue but was dependent on motivation. Whether performance decrements are due to constructs of fatigue or the effect of time on motivation is at this stage a rather abstruse point. However it is important to consider that heat and fatigue (motivation), as two forms of stress on subjects, may interact in some deterministic way. In the approach used for this study it is considered that exposure to heat will exacerbate the effects of fatigue over time.

Gibson, Allan, Lawson and Green (1979) looked at the effect on performance, in a flight simulation task, of differentially heating and cooling the skin temperature of subjects while Tcor was elevated to between 37.9 and 38.5°C. Their findings confirmed a number of other experimental conclusions (Allnutt and Allan, 1973; Allan and Gibson, 1979; Allan, Gibson and Green, 1979; Allan, Belyavin, Flick and Higenbottam, 1981 a and b) which indicate that skin temperature, its rate of change and direction, are closely related to feelings of comfort and discomfort which in turn are more closely related to performance than the absolute level of Tcor. This inverse relationship between subjective discomfort and performance indicates that performance may be a function of an affective or motivational state in the subject. One finding has been that performance during the phase where skin temperature is increasing towards the Tcor temperature is worse than during the phase where skin temperature is decreasing. It was argued by Allan and Gibson (1979) that the heating phase is perceived as a threat by the subject with a consequent unsettling effect on performance, whereas the cooling phase was perceived as a relief. These findings indicate that it is important to relate performance in some way to a motivational factor in the subject's affective state.

3. THE SEA KING INDEX OF THERMAL STRESS - SKITS

All indices of thermal stress attempt to relate the ambient environmental conditions to the extent of thermal stress or strain experienced by subjects. The Sea King Index of Thermal Stress (SKITS) is an attempt to derive guidelines for the tolerable exposure of RAN Sea King aircrew during low level operations (Hendy, 1985). The methodology for deriving the SKITS index was used to illustrate a number of considerations in the development of such an index and at the same time produce some interim guidance for squadron commanders on the impact of hot thermal conditions on the operational performance of aircrew. Although the rationale, techniques and method used may be found elsewhere (Hendy, op cit), an abbreviated description of the major features of the index and the SKITS predictions are presented here.

The major features of the methodology are:

a. the use of a multifactor linear regression model in which the independent variables are selected for their 'independence'; and

b. the presentation of the index in a probabilistic manner so that the decision of GO/NO-GO is clearly retained by the operational unit commander.

3.1 Development of the Index

The data on which SKITS is based were collected from 20 sorties by RAN Sea King helicopters flying from HMAS MELBOURNE, during the months of March to June 1977, while the ship was on passage from Australia to the United Kingdom (Rebbechi and Edwards, 1979). The data consisted of ambient temperature (Tdb and relative humidity) on the flight deck of the aircraft carrier and various temperatures in the cockpit and cabin of the aircraft during the sortie. From these data a WBGT for the cockpit and cabin were computed, using the form:

$$WBGT = 0.7\ Twbp + 0.3\ Tg.$$

Because the cockpit demonstrated a more severe environment, the cockpit WBGT was selected as the dependent variable for SKITS. It was found that the carrier flight deck Tdb accounted for the greatest proportion of the variance in the cockpit WBGT temperatures. The carrier flight deck wet bulb temperature was highly correlated with Tdb and as a consequence the wet bulb temperature was omitted from the multiple regression model due to the lack of independence, and therefore predictive power, of this variable.

The predicted cockpit WBGT for the Sea King aircraft (or SKITS) is therefore related to the dry-bulb temperature at the point from which the aircraft departs. The following function was derived for the index:

$$SKITS = 0.67\ Tdb + 11.4\ (^{\circ}C).$$

Using this relationship it is possible to calculate predicted cockpit WBGT as a function of ground (point of departure) ambient temperature. Limits might then be set on tolerable mean cockpit WBGT for normal, caution and danger zones of operation. Nunneley and Stribley (1979) produced guidelines of this type for their Fighter Index of Thermal Stress (FITS). The caution zone for FITS is bounded by 32.0°C and 38.0°C predicted cockpit WBGT, and covers conditions which are thought to be physiologically compensable if adequate hydration is maintained. The danger zone, above 38.0°C on the FITS chart, produces progressive heat storage, with associated effects of reduced performance and reduced tolerance to other stressors such as acceleration and hypoxia (Nunneley and Stribley, 1978). Similar limits could be adopted for SKITS.

3.2 A Risk Based Index

Rather than express the SKITS guidelines in terms of a variable (eg predicted WBGT) with little intrinsic meaning to field commanders, it was decided to reframe SKITS in terms of 'risk'. The residuals from the regression analysis of cockpit WBGT for the Sea King were used to define the uncertainty (ie variance) in the observed values of cockpit WBGT which was not accounted for by the linear model. Therefore, the risk-based SKITS model for predicted cockpit WBGT was assumed to consist of the linear model from the regression analysis, together with the variability about the regression equation as estimated from the probability density function of the residuals. This composite model was then used to predict

the probability that cockpit WBGT would exceed various limit values. The probability was calculated by determining the proportion of the area of the assumed normally distributed residuals which exceeded the threshold limit values (see Figure 1) used in the FITS criteria, ie, 32.0, 38.0 and 46.0° WBGT, for various values of the independent variable. Exceedances at the 32.0°C value are given the label of 'risk of minor performance loss'; 38.0°C - 'risk of major performance loss' and 46.0°C - 'risk of heat illness'.

Zones of normal, cautionary and dangerous operation can now be defined which are based on a tolerable level of risk. **For the purposes of demonstration only**, the upper bounds of the 'Normal', 'Caution' and 'Danger' zones are as follows .

Zone	Criteria
Normal	Risk of minor performance loss exceeds 0.5 (1 in 2)
Caution	Risk of major performance loss exceeds 0.1 (1 in 10)
Danger	Risk of heat illness exceeds 0.002 (1 in 500)

3.3 Interim Guidance for Sea King Hot Weather Operations

Table 1 presents the information on interim guidance for hot weather operations in the Sea King from the risk-based SKITS. The Normal, Caution and Danger zones are set in accordance with the risk based criteria presented above. These zones do not, in general, coincide with the predicted cockpit WBGTs used in FITS. The following qualifications are associated with this Table.

a. Commanders should ensure that aircrew are given time to acclimatize to hot conditions and aircrew should avoid extreme physical exertion during the first days of exposure.

b. Aircrew should remain well hydrated by an intake of fluids past the point where thirst is satisfied.

c. The zones shown in Table 1 are not appropriate if aircrew are wearing NBC assemblies, immersion suits or other special clothing assemblies.

d. Commanders should be aware of the levels of risk which are tolerated in these guidelines.

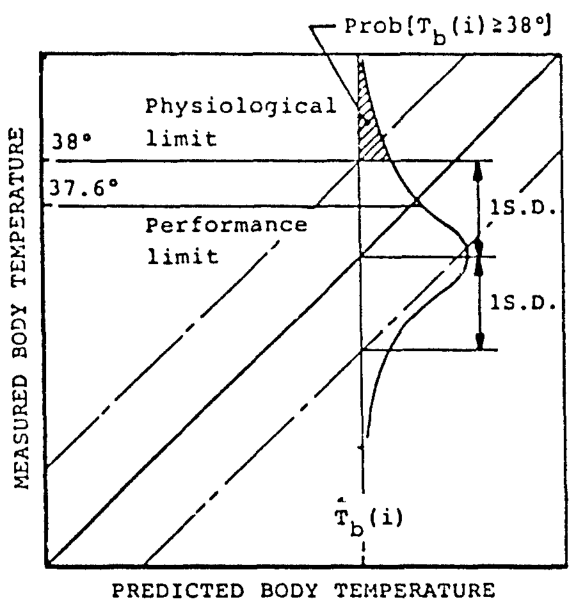


Figure 1. A probabilistic basis for thermal stress/strain index where Tb = body temperature and $\hat{T}$b = predicted body temperature.

Dry-bulb temp (°C)		SKITS (°C)	Risk of Minor Performance Loss	Risk of Major Performance Loss	Risk of Heat Illness
20.0	Normal zone	24.7	<0.001	<0.001	<0.001
22.5		26.4	0.004	<0.001	<0.001
25.0		28.1	0.032	<0.001	<0.001
27.5		29.8	0.144	<0.001	<0.001
30.0		31.4	0.395	0.001	<0.001
32.5	Caution Zone (i)	33.1	0.701	0.010	<0.001
35.0		34.8	0.967	0.063	<0.001
37.5	Danger Zone (ii)	36.4	0.983	0.230	<0.001
40.0		38.1	0.998	0.523	<0.001
42.5		39.8	>0.999	0.803	0.002
45.0	Extreme Danger (iii)	41.4	>0.999	0.950	0.015
47.5		43.1	>0.999	0.993	0.086
50.0		44.8	>0.999	>0.999	0.284
52.5		46.5	>0.999	>0.999	0.589

Notes:

(i) Caution Zone

1. Be aware of heat stress.
2. Limit ground period (pre-flight plus ground standby) to 90 min.
3. Minimum 2 hour recovery between flights.

(ii) Danger Zone

1. Cancel low level flights (<3000 ft AGL).
2. Limit ground period to 45 min.
3. Minimum 2 hours recovery between flights.

(iii) Extreme Danger Zone

1. Cancel all non-essential flights.

Table 1. **Interim guidance for hot weather Sea King operations based on SKITS values.** (See Section 3.4 in the text for caveats on the application of this information.)

3.4 Interpretation of SKITS

There are two aspects to consider in implementing the guidelines of Table 1, viz :

(i) the probability of exceeding a particular environmental state, eg a value of cockpit WBGT; and

(ii) the effect that this exceedance will have on the safety of the operation, eg the probability that a minor or major (these terms have yet to be defined) performance loss will result in an accident or an incident or would otherwise jeopardize the operation.

Hence it is the combined effect of these two factors which must be assessed in applying this Table. However, as the relationship between WBGT and performance is not clearly understood, slavish adherence to guidelines such as those found in Table 1 would be ill advised. It should be noted that the greatest confidence can be placed on an index which is derived from a variable which has a more firmly established link with performance; eg ideally this would be a performance variable with a known dependency on the thermal environment, but even core temperature would have been better than WBGT if data had been available. Even with these qualifications, Table 1 provides rational guidelines for hot weather operations in the absence of better data.

In setting the limit zones for FITS, Stribley and Nunneley (1978) argued that below 32.0°C cockpit WBGT, performance losses would be small or non-existent, but at 32.0°C WBGT a point is reached where decreased learning ability and cumulative fatigue may occur. For SKITS this point is labelled 'minor performance loss' and it is expected that exceedances at this level may result in small but reversible errors or omissions in procedures. Stribley and Nunneley (op cit) set 38.0°C WBGT as the point at which they believe aircrew physiological compensatory mechanisms will be insufficient to prevent cumulative heat storage. At this point one might expect a more general degradation in performance (Grether, 1973), particularly in those areas involving high STM load or in those tasks which require new or novel responses. Because of the likelihood of a more pervasive degradation, SKITS exceedances at the 38.0°C WBGT level were labelled 'probability of a major performance loss'. Finally, Stribley and Nunneley set 46.0°C cockpit WBGT as the limit for all non-essential flying. In SKITS this point is assumed to represent a level of environmental stress at which there is a real danger of thermally induced illness or physiological damage.

It is stressed that the zones in Table 1 are presented for interim guidance only as the best currently available information. FITS was developed for air-conditioned fighter aircraft in which the taxi stages of less than half an hour were described as 'hot' and the low-level flight time of 1 to 2 hours was described as warm. In the Sea King, the in-flight conditions may be little different from those during taxi and the sortie time may be well in excess of two hours on occasions, as indicated by the 6-hour exposure time chosen for the experimental exposure. The FITS table (Nunneley and Stribley, 1979) carries the proviso that it is not to be used when chemical defence, immersion, or arctic flight equipment is worn. Sea King aircrew routinely wear Mae Wests (as in the experiment) and these provide part of the effects of extra insulation and water-vapour impermeability attributable to immersion suits. Furthermore, Nunneley and Stribley (1979) stated that for the FITS caution zone of 32.0° to 38.0°C, core temperature would stablize below 38.0°C. This contrasts with the experiment to

be reported later (see Section 4) in which the WBGT had to be well below 32.0°C for core temperature in all subjects to stay below 38.0°C during a 6 hours exposure, in fact as low as 27.6°C. Thus there is the possibility that the caution and danger boundaries in Table 1 may need to be revised in the light of further work.

The decision tree which is appropriate for the use of the information in Table 1 is presented in Table 2. This Table indicates how the information could be used by squadron commanders.

4. THERMAL CHAMBER EXPERIMENT

With the demise of the proposal to air-condition the Sea King cabin and the slowing down of the Canadian Forces development of an LCG, there was a requirement to determine whether there were other cost effective methods available to ameliorate heat strain of aircrew during hot weather operations. One technique, which was considered to be worthy of investigation, was local cooling of the head and neck. Investigation of a number of different systems has been reported in the literature, for example : a water cooled cap under the aircrew helmet; the addition of shrouds to a cap for neck cooling; and a device for blowing cooled air across the face of the subject from ducts mounted on the helmet.

Numerous studies have discussed and demonstrated the virtues of cooling the head and neck as opposed to the whole body. Shvartz (1970) determined that a device cooling the head (12 per cent of the body's surface area) was more effective than cooling with a garment covering the trunk, arms and legs (60 per cent of the body's surface area). The findings from studies on different techniques of head cooling (Nunneley, Troutman and Webb, 1971; Kissen, Hall and Klemm, 1971; Kissen, Summers, Buehring, Alexander and Smedley, 1976; Kissen, Alexander, Smedley, Buehring, Ward and Lowe, 1976) generally indicate that :

a. sweat rate, as indicated by changes in body mass, is reduced by head cooling;

b. body core temperature, either measured rectally or in the auditory canal, shows a reduction due to head cooling; and

c. cardiovascular response to heat stress is reduced with head cooling.

Kissen, Hall and Klemm (1971) argued that because the facial area has a high preponderance of cold-sensitive thermoreceptors, and because peripheral neural inputs have an important effect on the hypothalamically mediated central control of thermoregulation, then the face is a particularly sensitive area through which thermal load and responses can be modified. Zakay, Shapiro, Epstein and Bril (1982) evaluated a range of personal cooling devices, including water and air cooled helmets and suits, a suit cooled by icepacks, jets of cooled air, and a fan circulating ambient air. The relative performance of each cooling technique was ranked according to a physiological stress parameter, a subjective comfort rating, an effectiveness evaluation and on the basis of the subject's cognitive performance. An overall ranking based on these four scales resulted in the icepak suit, which covered the torso, coming top of the list followed by jets of cooled air. Kissen et al (1976) found that blowing cooled air over the faces of their subjects was as effective in reducing Tre, heart rate (Hr) and sweat loss (SL) as was cooling the scalp and neck with a water cooled helmet liner and they therefore advocated face air cooling for the amelioration of heat stress.

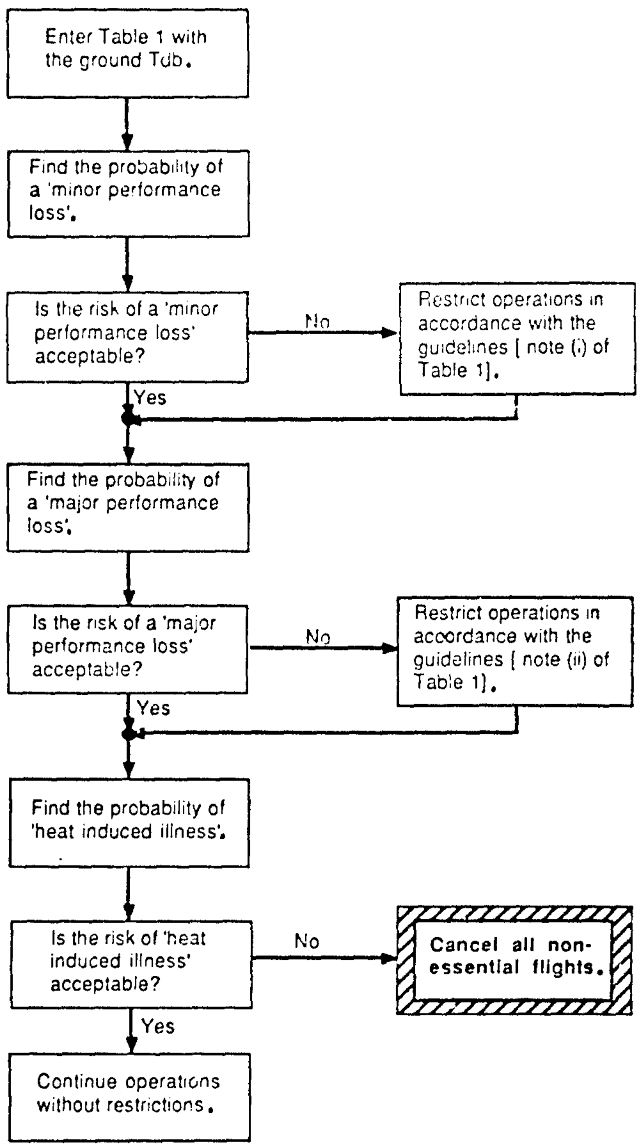


Table 2. Decision Tree for the interpretation of the risk-based SKITS.

Although helicopter pilots will often have either a clear or a tinted visor covering their forehead and eyes, there is still a considerable area of the face and neck exposed. Rear seat crew members in the Sea King (observer and sonar operator) generally operate with the visor up thus exposing a larger area of the face as a potential surface for cooling. The experiment reported here was designed to determine whether cooled air blown at the faces of aircrew would ameliorate the effects of heat stress and fatigue as measured by physiological, psychological mood and cognitive performance indices during a 6-hour exposure in a hot environment.

4.1 Method

Personnel from HMAS ALBATROSS provided the subject pool for the experiment. The experiment was conducted in two phases, the initial selection and training of subjects at HMAS ALBATROSS, and then the thermal exposure in the chamber at the RAAF Institute of Aviation Medicine, Point Cook. A medical protocol was established for the safety of the subjects and this dictated that exposure to the thermal conditions had to be terminated if:

a. the subject's core temperature, as measured in the ear canal adjacent to the tympanic membrane (Tac), exceeded 38.0°C;

b. the subject's Hr exceeded 140 beats/min;

c. the subject requested termination of the exposure; or

d. the attending medical practitioner directed termination of the exposure.

The environmental conditions originally chosen for the thermal chamber experiment were based on a prediction of the cockpit WBGT for the Sea King helicopter during low level operations in a hot, Australian mainland environment (Hendy and Manton, 1984). Broome airfield in Western Australia was selected as representing a severe environment for which data were readily available (McCrae, 1981) and from these data the value of the dry-bulb temperature which is exceeded on approximately 10 per cent of the total time at this location was obtained. The 10 per cent criterion value obtained for Broome (32.0°C), is exceeded at NAS Nowra on approximately 3 per cent of days in the year. At a dry-bulb temperature of 32.0°C, the SKITS value during low level flight is approximately 33.0°C WBGT. The conditions chosen to achieve this nominal WBGT value in the chamber were a Tdb of 38.0°C, Twbn of 30.0°C and a Tg of 39.3°C. Using the form:

$$WBGT = 0.7Twbn + 0.2\,Tg + 0.1Tdb,$$

these values give a WBGT of 32.7°C, which is consistent with the predicted conditions in the Sea King cockpit at the 10.0 per cent criterion for Broome. The radiant component was achieved by the use of a two bar (750 and 1000 watt) radiant heater. The subjects were seated in an area of the chamber in which there was no perceptible air movement apart from that of the blown cool air when provided as part of the experimental conditions. However, on the first two days that subjects were exposed to this temperature without blown cool air, some exposure durations were as brief as 60 to 90 min before Tac values exceeded 38.0°C (see Figures 2 and 3) with a consequent premature termination of the exposure. Therefore chamber conditions were modified for the remaining experimental runs to a WBGT of 27.6°C which was achieved with a Tdb of 36.0°C,

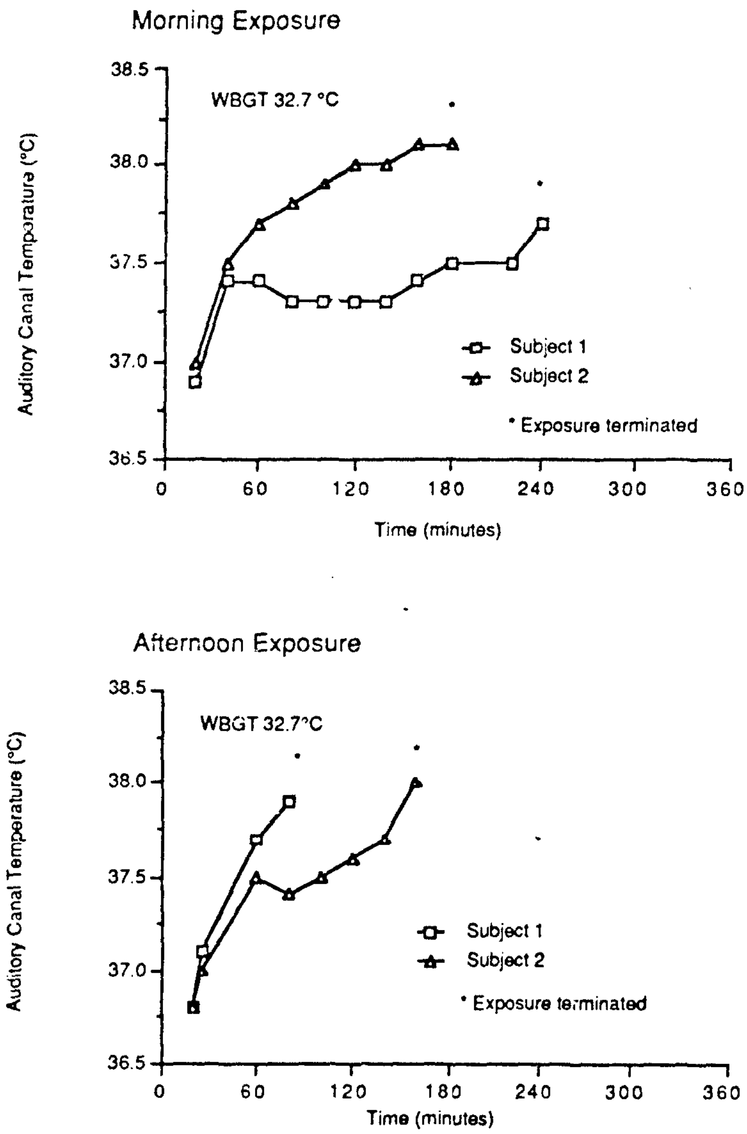
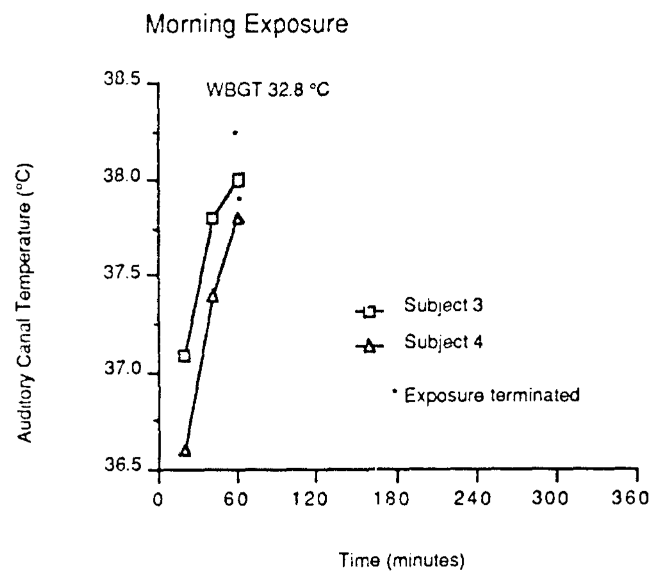


Figure 2. **Auditory canal temperature for the first pair of subjects when the WBGT in the thermal chamber was 32.7°C.**



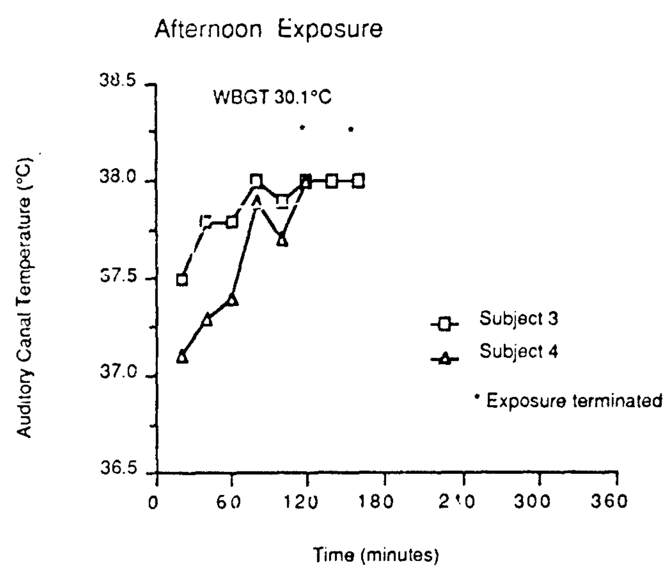


Figure 3. **Auditory canal temperature for the second pair of subjects when thermal chamber temperature was 32.7°C in the morning run and 30.1°C in the afternoon.**

Twbn of 24.0°C and with no elevation in the black globe temperature. This arbitrary departure from the planned exposure conditions was deemed to be necessary in order to avoid repeated premature terminations of the exposures. The modified conditions represent a relatively mild environment and yet two subjects were just able to experience a full 360 min exposure without exceeding a Tac of 38.0°C.

On the afternoon before their scheduled exposure in the thermal chamber subjects were given a medical examination, and in the evening they performed two practice sessions on the performance tasks. Each subject had practised the performance tasks over a period of a fortnight before the start of the thermal chamber exposures during the first phase of the experiment. These practice sessions were designed to establish a stable level of performance so that the data collected in the thermal chamber were not expected to be affected by the highly variable performance which is characteristic during initial learning of new tasks.

Two groups of 6 subjects were exposed, two at a time, to the modified (ie 27.6°C WBGT) thermal conditions. All subjects were dressed in standard summer Sea King aircrew equipment assemblies, comprising :

a. Nomex one piece coveralls;

b. socks and boots;

c. life preserver unit (Mae West);

d. SPH-4 helmet;

e. cotton or synthetic T shirt or singlet;

f. cotton or synthetic underpants; and

g. flying gloves.

During the exposure, subjects were seated on standard Sea King crew seats with the 5 point restraint harness and dinghy pack correctly fastened. The crew seats were attached to workstations on which various control sticks, keyboards, and video monitors were mounted.

One of the groups of subjects, the experimental group, had cooled air (12.0 to 15.0°C at the nozzle outlet) directed at their faces. The air was delivered to each subject through a nozzle that was designed to reduce the entrainment of ambient air into the cooled air stream (Hughes, 1981). The nozzle was situated approximately 800 mm away from the subject's head and the air velocity at this point in the central core was measured at 1.5 m/s. The control group did not experience the cooled air stream: indeed, the nozzles and associated ducting were removed from the chamber and care was taken to keep knowledge of the cooled air condition from the control group.

Exposure to heat causes physiological changes to occur in subjects. The better acclimatized a subject is to heat the less physiological strain he will experience in a given exposure (Lind, 1964). The raising of body temperature by any means, including physical exercise, will produce changes over time which we associate with acclimatization to heat (Clark and Edholm, 1985). Therefore one of the indices of the level of heat acclimatization could be taken as the level of

physical fitness of the subject. The two groups of subjects, in this experiment, were matched with each other in terms of their cardio-respiratory fitness in order to control for the level of acclimatization across groups. During phase one of the experiment at HMAS ALBATROSS, cardio-respiratory fitness was determined for each subject using the method specified by the Director General of Air Force Health Services. This method is based on the predicted oxygen uptake related to a measured Hr and a physical workload, adjusted for age and mass (Astrand and Rodahl, 1970).

4.2 Measured Variables

The variables that were measured during the experiment fell into three general areas covering physiological and biochemical variables, psychological mood variables and cognitive performance variables.

4.2.1 Physiological and biochemical variables

A number of sites for core temperature measurement was rejected on practical grounds alone. For example, the need to communicate and the length of the experimental exposure made esophagal and sublingual measurements unsuitable. The use of a radio pill was considered not to be a viable option because of the possible excursion of the pill during the 6 hours of the experiment. Of the remaining possibilities, the auditory canal was selected as the preferred site for the measurement of core temperature in this experiment, for reasons of subject acceptability, the supposed relevance of head temperature to thermoregulation, and the possible greater sensitivity of head temperature to the experimental manipulations.

Heart rate was obtained using a 3 lead ECG electrode pattern (left and right chest, abdominal reference electrode) driving a Beckmann cardiotachometer coupler 9857 (0.25 mm/s, x1, 0.3 Hz). Auditory canal temperature was measured using Yellow Springs thermistors (YSI 44005), calibrated on, and read from, a Light Industries Mini-Lab meter. The auditory canal probe was inserted into the external auditory meatus until pressure on the tympanic membrane was reported by the subject. The probe was then withdrawn slightly so that pressure on the probe, from the helmet, would not cause the subject pronounced discomfort. The thermistor in the ear canal was kept in place by a plastic form-fitting ear plug over which was placed a 150 mm by 150 mm patch of cotton wool. The cotton wool was kept in place with tape and by the pressure from the SPH-4 helmet's integral ear muffs. This was regarded as sufficient insulation to shield the thermistor from the ambient conditions in the thermal chamber. The Hr and Tac parameters were recorded every 5 min during exposure to the thermal conditions. Urine samples were also collected during the chamber trials and these were analysed for components which would indicate the physiological reaction of the body's fluid and stress mechanisms to the thermal conditions. The variables assayed in the urine samples were:

a. urea;

b. sodium (Na);

c. potassium (K);

d. adrenaline (Ad);

e. noradrenaline (NorAd);

f. dopamine (Dop);

g. the 17-ketosteroids (17-Ket); and

h. creatinine.

4.2.2 Subjective Report Scales

Three subjective report scales were filled out by subjects during exposure to the hot conditions in the chamber. They were filled out at the start of the chamber exposure, half way through and then just before the last cognitive performance testing session at the end of the exposure. One scale was the Thermal Rating Scale where subjects were asked to indicate how they felt by marking a 100 mm line bounded by the descriptors 'thermally comfortable' and 'thermally intolerable' (Allan and Gibson, 1979). The two other scales were presented as Mood Scales. Mood Scale 1 was developed by Norris (1971) and consisted of sixteen 100 mm lines, each one bounded by antithetic adjectives. A subsequent factor analysis of this scale (Herbert, Johns and Dore, 1976) revealed two orthogonal factors, which have been called 'alertness' and 'calmness' for this study Mood Scale 2 measures subjective fatigue on three scales. These were 'nervous fatigue', 'drowsy fatigue' and 'exhausted fatigue' (Wolf, 1967).

4.2.3 Cognitive performance measures

Three cognitive performance measures were used in the experiment. These were the Hysteresis task, the Manikin task and the Atari video game called 'River Raid'. The Hysteresis task (Cumming and Croft, 1973) is considered to measure the point at which short term memory becomes overloaded during a period of increasing task demand and it also provides information on the dynamics of information processing recovery from overload during a period of decreasing task demand (Goldberg and Stewart, 1980). In the version of the task used in this experiment, the subject was presented with a visual stimulus of the digits 0 to 9 on a vector graphics (calligraphic) display, and he was required to respond to as many of the stimuli as was possible with a corresponding key press on a special key pad. The rate of presentation of the digits increased linearly from 0 to 3 digits per second over 18 seconds and then decreased, also linearly, to the initial value over the next 18 seconds. Each trial consisted of two of these presentation cycles run consecutively. At each testing session three trials were completed with a 15 s break between trials. Subjects used a special keyboard with a response button, corresponding to one of the numerals 0 to 9, located under every finger and the thumbs of both hands. The training period in the first phase of the experiment was designed to make subjects familiar with the keyboard so that they could use it in a 'touch-typing' manner and thereby allow their eyes to be kept on the display. Scoring followed Croft's (1971) procedure which was to split each presentation cycle up into 19 equal time segments and to determine the correct number of subject responses to the displayed digit string in each of these segments. The scores used for the analysis were recorded in terms of the mean presentation rate for the segment adjusted for the proportion of correct responses (digits/s) within each segment. Data were pooled across cycles and trials within each testing session.

The Manikin task involves spatial ability (Carter and Woldstad, 1985) and has been used before in thermal stress experiments (Nunneley, Reader and Maldonado, 1982). In this experiment the simplified image of a human figure with outstretched arms was presented on the vector graphics display. In one hand (either the left or the right) the manikin appeared to be holding a square object while in the other hand a circular object was displayed (see Figure 4). The manikin could be presented either upright or inverted and either facing towards or away from the subject. Below the manikin a square or a circle was presented and the subject had to indicate in which hand the manikin held the indicated shape. Subjects responded by pressing a button on the right side of the keyboard with the right hand for a 'right' response and a button on the left side of the keyboard with

the left hand for a 'left' response. Each presentation of the manikin lasted for 2 s with a 1 s pause before the next image was presented. A series of 96 presentations in a pseudorandom order, lasting for 4.8 min, constituted a trial. Only one trial was given at each training session and each testing session during the thermal chamber exposure. At the end of each trial and at the beginning of each new trial subjects were told their average response time and the number of correct responses to the 96 presentations they had previously completed.

Some video games have been evaluated as laboratory devices for measuring human performance (Kennedy, Bittner, Harbeson and Jones, 1982). The games which were tested demonstrated stable characteristics in repeated measures experiments and they involved the development and use of complex psychomotor skills. The games which were evaluated were apparently not commercially available in this country at the time of preparation for the experiment, but one closely resembling those described was selected from the range available. For this experiment, the video game 'River Raid' (marketed by the Atari Company) was played by subjects using a joystick with an integrated firing button, and with the visual display presented on a colour television monitor.

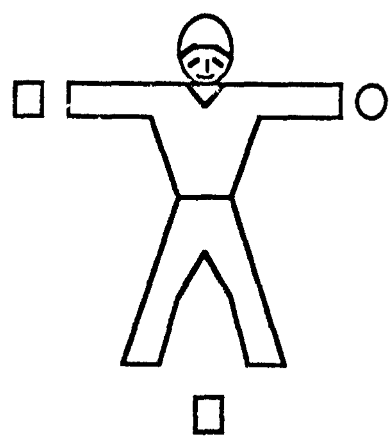


Figure 4. Image generated for the Manikin task.

Each subject was required to control a symbolic aircraft as it flew up a river. The subject could control the aircraft's speed and move it from left to right by means of the joystick. The subject had to control the aircraft so as to avoid the land on either side of the river, either destroy enemy vehicles or avoid them and shoot down bridges which appeared across the river from time to time. Subjects also had to deal with fuel management by maintaining an above zero reading on a fuel gauge. Fuel could be picked up at dumps located along the river and points were scored for shooting enemy vehicles, unused fuel dumps and bridges. The game became more difficult as subjects got further up the river. Subjects started the game with four aircraft and were given a bonus aircraft for each 10 thousand points scored. An aircraft was lost if it hit the river bank, another vehicle or a bridge, if it ran out of fuel or if it was hit by enemy fire. At each training session, except for the two on the evening prior to the chamber exposure, subjects played two complete games. For all other testing sessions subjects played one game only. The game was over when all aircraft were lost. The score recorded was the total score achieved at the end of the game.

4.3 Procedure

The schedule for the chamber experiments called for each pair of subjects to arrive at the laboratory at 8 am after having had breakfast by 7.15 am. They gave an initial urine sample and were then weighed. Before entering the chamber they drank 1 L of water or cordial and had Hr and Tac sensors mounted. Subjects then donned their flying clothing and entered the chamber at approximately 9 am. Some variations to this schedule were necessary to allow for equipment maintenance and connections with transport. The actual times of chamber entry for the two groups were 0800, 0900 and 0830 for the experimental group and 0900, 0900 and 0830 for the control group. Once strapped into their seats, and with the physiological sensors connected to the recording equipment, they completed a set of subjective report scales. As a warm-up on the cognitive tasks they then performed an abridged training session on each task. The schedule of testing sessions, administration of subjective report scales, and lunch are indicated in Figure 5. Testing sessions lasted approximately 30 to 40 mins depending on how long the game of River Raid took to complete. There was a break of between 15 to 25 min when subjects relaxed and read books before the next testing session started. Water was available ad lib during the chamber exposure. The volume of water consumed by each subject, urine volume and food intake were measured. Urine 'spot' samples, which consisted of all the urine passed at a particular time, were collected when subjects arrived at the laboratory, after 180 min in the chamber and immediately subjects left the chamber after 360 min. Each of these samples was mixed with 5 g of sulfamic acid crystals which acted as a preservative and part of each sample was then stored in a domestic refrigerator before being taken to a pathology laboratory for analysis. All urine collected, other than that stored and sent for analysis, was discarded after the volume had been measured. Subjects were not allowed to leave the laboratory until their Tac was seen to be decreasing and the medical practitioner had released them.

4.4 Results

The results of the experiment are categorised under the 3 classes of variables which were measured, viz:

- i physiological and biochemical;
- ii subjective comfort and mood scales; and
- iii cognitive performance.

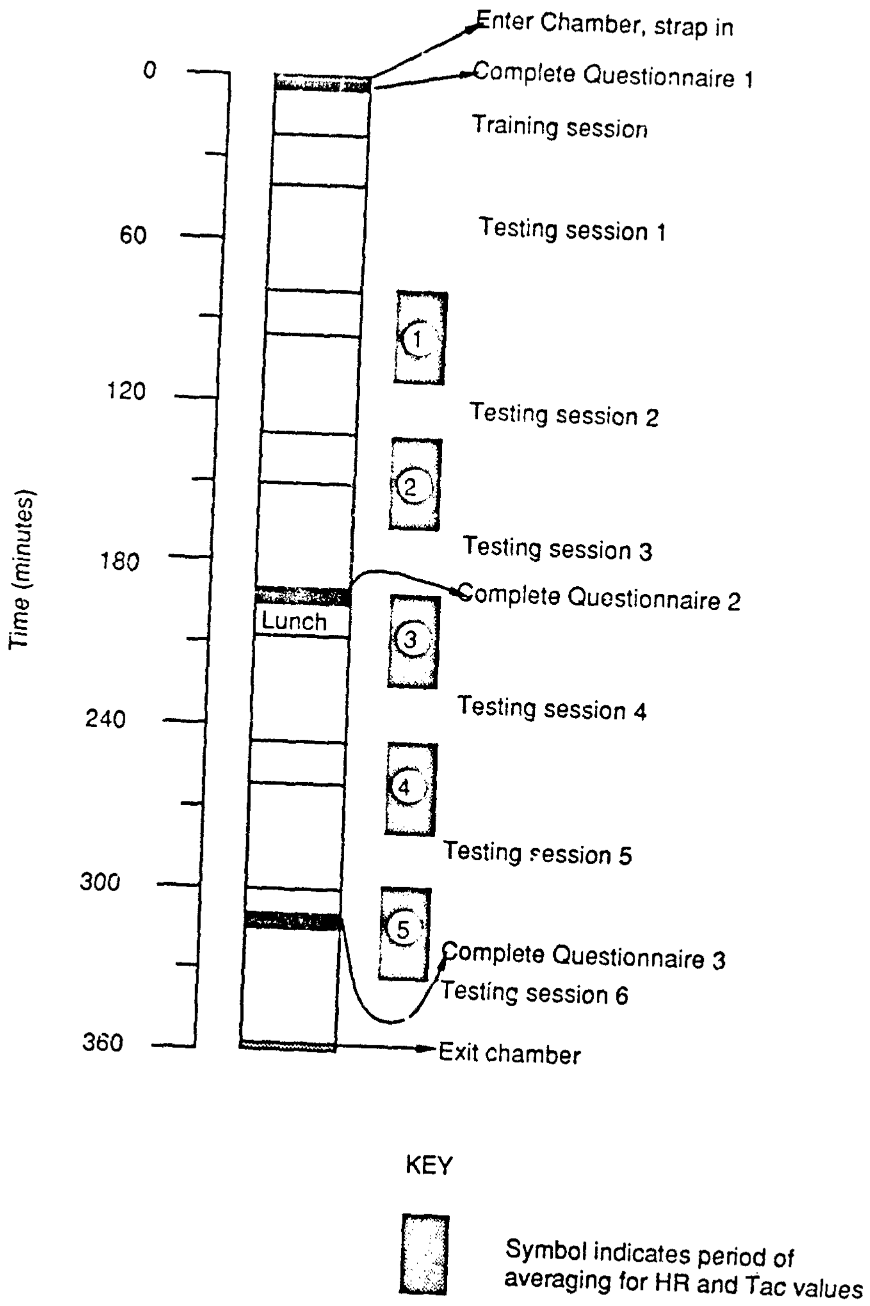


Figure 5. Schedule of events during the thermal chamber exposure.

In the figures that follow in this section, error bars have been included for added information. Where practicable standard deviations have been plotted and in some cases, for ease of presentation, standard errors have been used.

4.4.1 Physiological and biochemical variables

The data for Tac and Hr were averaged over five 30-min periods. The first period started 80 minutes after subjects entered the chamber, with successive periods commencing at the end of each testing session. Each period was chosen to cover the period of 'rest' between testing sessions and approximately the first 10 minutes of the testing session itself. The 80 minutes delay, which preceded the first averaging period, was to allow for the time constant of the sensor and the auditory canal air mass. Figure 6 shows the data plotted, with each data point located in the middle of the period over which it was averaged. The Hr data have been plotted as the mean percentage change in Hr based on the subject's resting Hr measured at the medical examination the day before.

An analysis of variance (ANOVA) of these data indicated that there was a statistically significant increase in both Tac and Hr over time ($p<0.001$). However, differences between the two groups and the group by time interaction were not statistically significant ($p>0.05$). It is interesting to note from Figure 6 that the control group had a consistently higher Tac than the experimental group and that the change in Hr for the control group over time was also slightly greater.

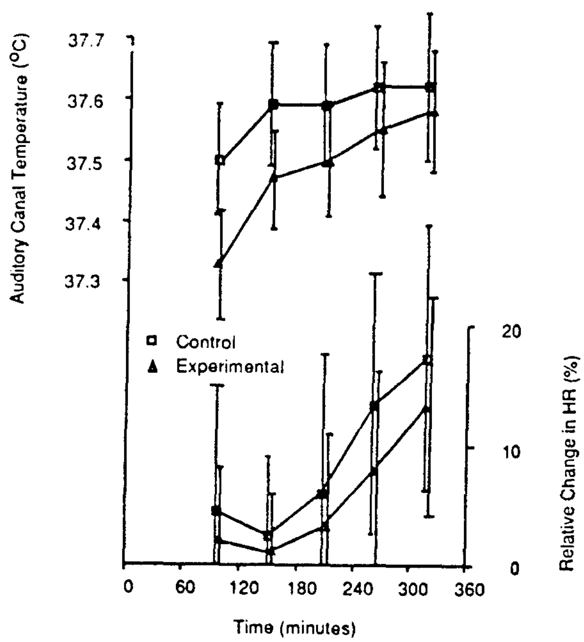


Figure 6. Mean auditory canal temperature and relative increase in heart rate plotted against time in the thermal chamber (vertical bars indicate standard error where N=6).

Calculation of sweat production (kg/hour), based on the pre-exposure and post-exposure body mass adjusted for the fluids and food consumed and the urine produced, indicated that the control group produced 47.0 per cent more sweat than the experimental group. This represents a significant difference between the two groups ($p<0.05$). The calculated Craig Index of Thermal Strain (Kissen, Summers, Buehring, Alexander and Smedley, 1976), which takes account of Hr at the end of the experiment and the change in Tac over the exposure period as well as sweat production, did not show a statistically reliable difference between the two groups ($p>0.05$).

Each of the variables analysed from the urine samples was adjusted to a quantity per 100 mmol of creantinine. The use of the creantinine-based ratio corrects for variations in the timing of the urine collections, and for the variations in the subjects' ages and body sizes (Storm, 1980). All variables were log transformed in order to linearize the variance for samples with low values. An ANOVA indicated that there were no significant changes in body mineral balance (Na, K and Na/K) over the exposure period or between groups ($p>0.05$). For the remaining analyses, there were no reliable differences between groups. The concentration of 17-Ket in the urine showed a significant trend over time ($p<0.01$) with a reduction in the concentration at the mid-term sample and an increase in the last sample. The other hormones had similar trends over time. An analysis of the ratio of NorAd/Ad was also conducted as it has been shown by Fibiger, Singer and Miller (1984) that a low ratio (a high proportion of Ad) is characteristic of mental effort, and a high ratio (a high proportion of NorAD) is characteristic of physical effort. The ANOVA indicated that there was a significant trend of the ratio over time ($p<0.02$). The data presented in Figure 7 indicate that the ratio decreases between the initial sample and the mid-term sample. The difference between the first sample and subsequent samples probably reflects the physical effort of getting up, having breakfast and reporting to the laboratory.

4.4.2 Subjective report scales

The ANOVA for the Thermal Rating scale indicated that there was a significant decrease in the level of subjectively rated thermal comfort over the exposure period ($p<0.001$). There was no statistical difference between the two groups on this variable. The alertness factor from Mood Scale 1 (see Figure 8) revealed a statistically significant decrease in subjective alertness over time ($p<0.001$) and a significant group by time interaction ($p<0.02$). This interaction is largely due to the numerically lower mean rating for alertness for the experimental group (higher 'alertness'), when compared to the control group at the start of the exposure period, changing to the other way around half way through the exposure. The results for the calmness scale indicate a statistically significant decrease in this variable over time ($p<0.001$) for both groups.

The data for Mood Scale 2 were converted to ranks and analysed using non-parametric statistical tests. A series of Mann-Whitney U tests revealed that there were no statistically reliable differences between the two groups at any of the three sampling times for the nervous fatigue, drowsy fatigue or exhausted fatigue scales ($p>0.05$). Data for the two groups were therefore pooled and analysed by a Friedman two-way analysis of variance to test for a trend over time. This test indicated that there was a significant increase in the subjective rating of exhausted fatigue symptoms over the exposure period ($p<0.004$).

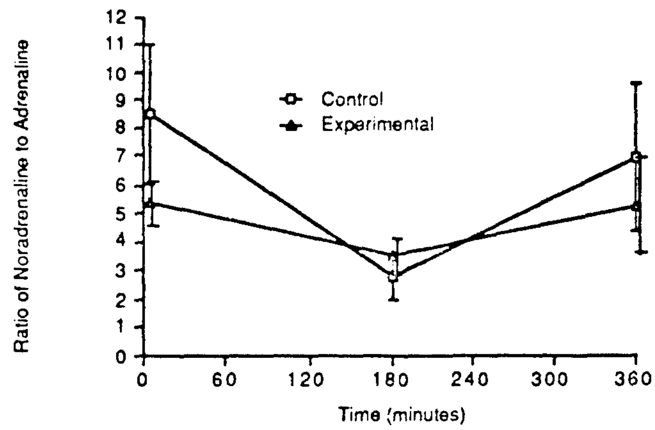


Figure 7. The ratio of noradrenaline to adrenaline (vertical bars indicate standard error where N = 6).

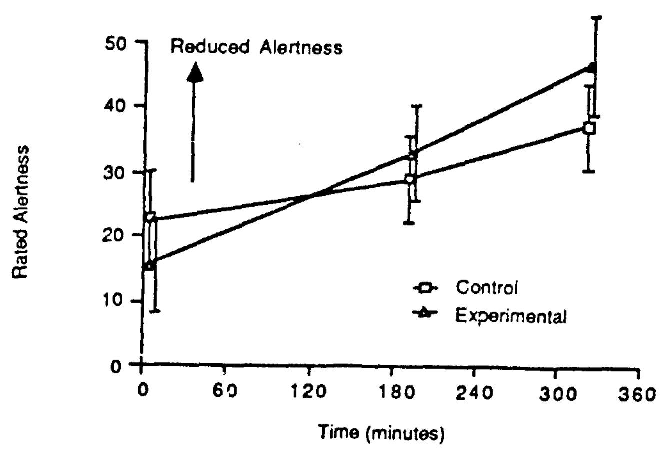


Figure 8. The alertness factor from Mood Scale 1 plotted against exposure time (vertical bars indicate standard deviations).

4.4.3 Cognitive Performance Measures

A plot of a sample of Hysteresis data is shown in Figure 9. Three variables were taken from the data collected. One was the point at which the subect was transmitting the maximum number of digit/s (Trx-max). The second variable was the number of digit/s being transmitted when the presentation rate was at its maximum (Pres-max). The last variable was the area between the performance curve during the increasing presentation rate and the curve for performance during the decreasing presentation rate (Area). A separate ANOVA for each of these variables did not indicate any statistically reliable change in performance over time of between groups (p>0.05). Nevertheless the findings confirm the phenomenon of a hysteresis in the recovery of operator performance after overload. The robustness of the phenomenon indicates that this task may well be useful in the study of operator performance in a dynamic workload environment.

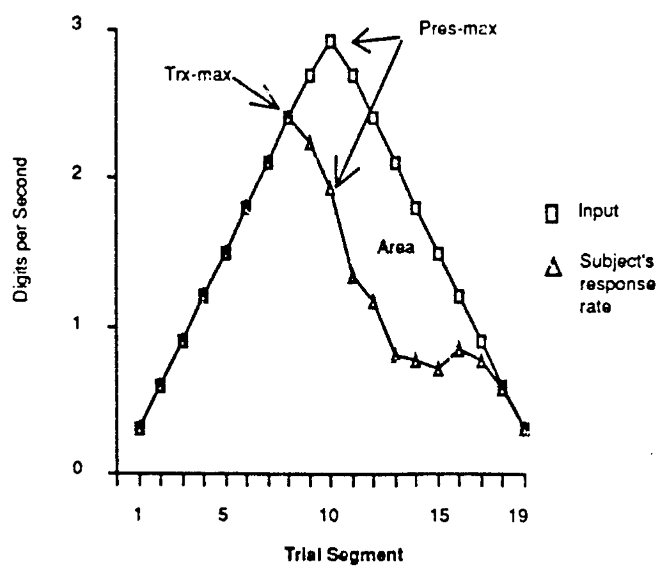


Figure 9. Variables in the Hysteresis task

In an initial inspection of the data from the Manikin Task it was noticed that there was a consistent difference between the groups in their mean reaction time scores. It was also apparent that a formal test of the homogeneity of the within cell variance between groups was required. A test provided by Levine (1960) as discussed by Keppel (1973), which is relatively insensitive to departures from normality, was used. The test indicated that there was a statistically significant inequality of the variance between the two groups ($p<0.001$). The experimental group, who experienced the blown cooled air, had a within cell variance which was far higher than the control group. A logarithmic transformation of the reaction time scores failed to overcome this problem. However, the between cell variances were homogeneous within groups. Further inspection of the data for the training sessions, collected before the thermal chamber exposure, indicated that both the mean and variance differences between the two groups were present prior to the experimental manipulation. The balancing of the two groups of subjects was based on aerobic fitness and not performance on this test. The failure to balance the groups in the Manikin Task performance must therefore be considered as sampling error with the consequence that it is not possible to compare their performance directly. A plot of the reaction time means are shown in Figure 10. A one way ANOVA was conducted on each group's data, both for the reaction time and error scores, to determine whether there was an effect on performance over the thermal exposure. All ANOVA results indicated that there was no statistically significant effect of the length of the exposure on performance.

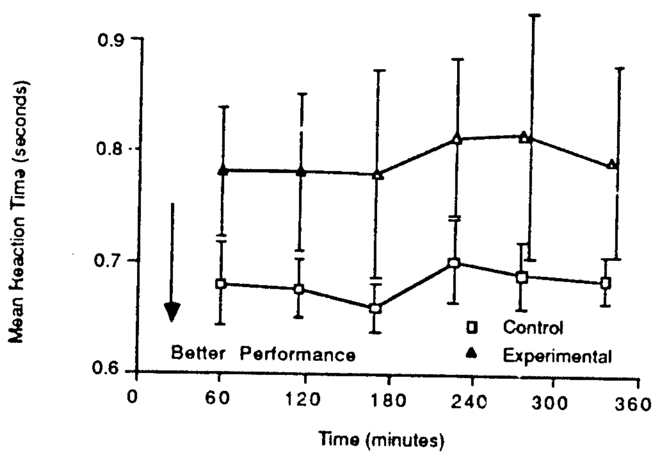


Figure 10. Mean reaction time for the Manikin task plotted against time of testing session (vertical bars indicate standard deviations).

Analysis of the River Raid data by ANOVA indicated that there was an improvement in scores over the exposure but at a low level of significance ($p<0.10$). This trend is apparent in Figure 11. No other effects reached statistical significance.

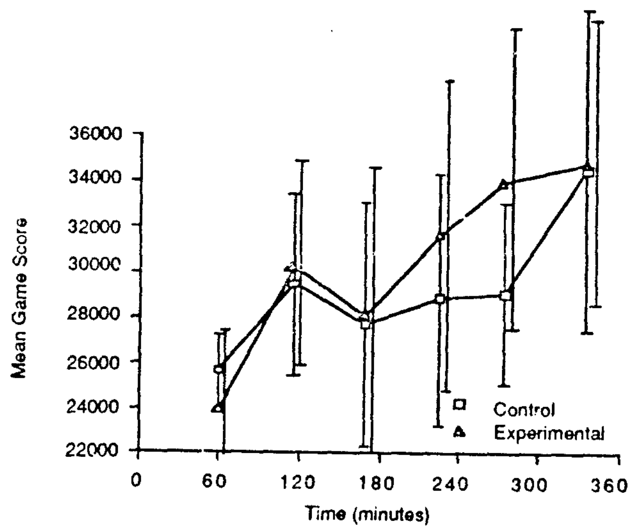


Figure 11. **Mean performance on the video game River Raid plotted against testing session (vertical bars indicate standard error where N=6).**

4.5 Discussion

The physiological variable of sweat production indicates that blown cool air in this experiment reduced the level of thermal strain experienced by the subjects in the experimental group compared to those of the control group. This finding is important in that it was apparent even in the relatively mild thermal conditions that were experienced. There was no indication that the blown cool air condition reduced the effects of fatigue as measured by the other variables in the experiment, and both of the groups showed significant signs of fatigue-related effects over time.

Apart from sweat production the other physiological and biochemical variables have trends that are consistent with an increase in physiological strain over time, but they were not sufficiently sensitive to differentiate between the two groups. The Subjective Report Scale findings indicate that there was a consistent subjective reduction in thermal comfort, alertness and calmness over the 360 min exposure. The subjective rating of exhausted fatigue showed a consistent increase over the exposure and the failure of the nervous and drowsy fatigue scales to show a time-related effect indicate that fatigue was related to physical tiredness rather than mental tiredness. This conclusion is borne out by the increase in Hr over the exposure which indicated greater physical effort. Therefore it may be concluded that the principal physiological response in the experiment was an increased cardiovascular effort associated with the reaction to the thermal conditions.

The results of the cognitive performance measures indicate that short-term memory capacity and recovery after overload were not significantly affected by 360 min exposure to the thermal conditions. The performance on the video game indicates that improvement with practice was still taking place during the six testing sessions. Subjects were generally highly motivated by this game and there was some rivalry apparent between subjects. The game was somewhat different in nature from the other two cognitive measures as it utilised the development of a game strategy through the training phase which required a changing psychomotor response depending on the game situations that developed. This game could be regarded as a measure of skilled performance at a holistic level which is somewhat different from the requirements for short-term memory and spatial orientation ability in the other tasks. The results of the Manikin task indicate that spatial ability was not reliably affected during the exposure to the thermal condition.

It should be remembered that the conditions in the thermal chamber for this experiment were relatively mild. The equation for SKITS indicates that the 27.6°C WBGT used in the chamber would be exceeded in the aircraft when the ambient air temperature (Tdb) at ground level was above 23.5°C. (This value for the ambient temperature is exceeded on 35.0 per cent of the days at HMAS ALBATROSS.) Over the exposure period one subject reached a Tac of 38.0°C and two others were within 0.2° of reaching 38.0°C. In hotter conditions than this, substantial heat storage may occur due to the inability of the body's thermoregulatory system to maintain a stable core temperature. It is hypothesised that Sea King aircrews' Tac may increase by amounts of practical significance on sorties where the ambient ground level Tdb is above 24.0°C and at higher temperatures, say above 30.0°C Tdb (SKITS = 31.4), Tac may regularly exceed 38.0°C. It is at these higher temperatures that significant physiological and performance changes occur and these may have important implications for long term operations with high sortie rates in tropical and subtropical environments. The findings of this experiment underline the critical issue of the need to ameliorate heat stress in hotter environments.

The findings of this experiment indicate that there is considerable variation between subjects in their response to the thermal conditions. So that subjects could thermoregulate at and below at Tac of 38.0°C, the temperature in the thermal chamber was initially set at approximately 32.7°C WBGT based on the recommendations from the FITS table (Stribley and Nunneley, 1979). However, with this chamber temperature three out of the four subjects were unable to thermoregulate below 38.0°C with up to three hours exposure to the thermal conditions (see Figures 2 and 3) and two of the subjects were only able to stay in the chamber for 80 minutes before exceeding the critical Tac value. This finding is somewhat at odds with the recommendation of FITS. The difference between our thermal chamber temperature and a FITS temperature at which thermoregulation below 38.0°C Tac should occur ranges between approximately 4.0 to 10.0°C WBGT. This important difference is confusing in that Stribley and Nunneley go to some lengths to support their choice of the limits for the caution zone in the FITS table (32.0 to 38.0°C) from the available literature.

The results of this experiment do not challenge the claim (Stribley and Nunneley 1978) that performance losses would be negligible below 32.0°C WBGT. However, it is apparent that over the duration of these exposures, significant heat storage occurred in conditions far less severe than those tolerated in FITS. To satisfy the core temperature requirement for SKITS, given a sortie duration of up to six hours, it would appear that the upper limit on the normal zone should be reduced from 32.0°C to around 27.0°C WBGT. This should allow most aircrew to

thermoregulate below the World Health Organisation's recommended maximum core temperature of 38.0°C (Dukes-Dobos and Henschel, 1973). It is likely that the limit values for the 'Danger' and 'Extreme Danger' zones should be modified as well; however, the data from this experiment does not provide the necessary information.

A likely explanation for the severity of the physiological response in this experiment concerns the clothing assembly worn by subjects. The assemblies worn, combined with the aircraft seat and harness, severely restricted the surface area available for heat exchange due to evaporative sweat loss. This points to the need to conduct experimental investigations in environments which are representative of the operational situation, and highlights the potential for error when extrapolating experimental data from lightly clothed subjects exercising on treadmills or stationary exercise bicycles.

One further point which may be contributing to the difference in the prediction based on the FITS criterion and our experiment is the WBGT index itself. Kerslake (1982) indicated that the use of the WBGT index outside the application for which it was designed may be indefensible. The application of WBGT should be confined to the range 29.0 to 32.0°C and should only be used to indicate the potential hazard to physically fit young men lightly clad and involved in army training or similar activities. He stressed that outside this range of temperatures WBGT has no significance. Kerslake (1972) cited some research which indicates that there is a poor relationship between WBGT and measurements of physiological strain. However the index has been used extensively by many protagonists in aviation related thermal research and the pressure to gather data which allows comparison across studies is therefore strong. While the WBGT index is simple to compute it is apparent that other indices of heat stress are perhaps more appropriate to this type of work. The Predicted 4-Hour Sweat Rate (Kerslake, 1972) is based on an empirically derived nomogram which indicates the predicted sweat rate over a 4 hour period. As this period is comparable with the sortie durations for which the RAN is interested it would be appropriate to investigate the use of this index further for a SKITS-type application.

The results of this study indicate that amelioration of sweat rate is feasible using a cooled air stream directed at the subject's head. However under the conditions studied there was no indication that Tac was significantly lessened. Kissen, Summers, Buehring, Alexander and Smedly (1976) found that blowing cooled air over the face of the subjects was as effective in reducing rectal temperature as cooling the scalp and neck of their subjects with a water-cooled helmet liner. The environmental conditions used by Kissen et al were more severe than were those used in the experiment reported here (Tdb = 46.0°C, Twb = 33.7°C). The helmet used in the Kissen et al experiments was modified so that the cooled air was passed across the face from outlets attached to the helmet, the outlets being on either side at eye level and underneath the helmet visor when it was deployed. In the present experiment subjects did not have their visors down, so the whole face was exposed to the cool air stream. Having the visor(s) deployed would blank off a considerable proportion of the available exposed skin area and could be expected to reduce the effect of cooled air from a cockpit coaming-mounted outlet. Provision of a modified helmet, like the one described by Kissen et al (1976), may be required in order to gain reasonable stress amelioration for aircrew who fly with the visor(s) deployed. Nevertheless the written comments solicited from subjects in this experiment on their reaction to the cooled blown air was unanimously favourable. Operational trials would be required to demonstrate the practical feasibility, benefits and disadvantages of blown cool air from coaming- and helmet-mounted nozzles.

4.6 Conclusions and Comments from Experiment

The major conclusions from this experiment are:

a. Subjects were unable to thermoregulate at or below a Tcor of 38.0°C while wearing aircrew clothing and survival equipment in a thermal environment equivalent to the Sea King aircraft operating from an airfield in the tropics 10 per cent of the time.

b. Blown cooled air directed at the face and neck area of aircrew, in mild thermal conditions, decreased their sweat rate.

c. Subjective ratings of thermal comfort, alertness and calmness decrease, and ratings of exhausted fatigue increased over time in relatively mild heat.

d. Skilled performance did not appear to be affected by fatigue factors of the degree experienced in the experiment.

e. Aircrew core temperatures probably exceed 38.0°C in low level, three to five hour sorties, on days when ground temperatures are in the vicinity of 24.0°C.

f. Although the low entrainment nozzle appeared to work well, an alternative system for delivery of cooled air to the face may have to be investigated for aircrew who fly with a visor on their helmet deployed.

5. FURTHER DISCUSSION

The failure of subjects' performance to be affected by the thermal conditions experienced requires some further examination. The sensitivity of different types of performance measures to the effects of fatigue and the magnitude of the fatigue affect required to produce measurable changes in performance are discussed.

5.1 Fatigue and Heat Stress

In the earlier sections of this report it was indicated that the underlying experimental hypothesis being examined was that exposure to an environment which caused a stress response may, over time, lead to a decrease in the effectiveness of aircrew and/or the availability of the ASW aircraft. In practical terms this hypothesis would predict that during periods of sustained operations lasting for weeks, where adequate periods of recovery may not be possible, then the compounding effects of heat stress may exacerbate the cumulative effects of fatigue. The current research indicates that exposure to mild thermal conditions for a six hour period causes aircrew to demonstrate a physiological stress response. Although the cognitive performance variables show little, and in some cases no, statistically significant degradation over this period, subjective reaction indicated a significant change in mood and feelings of fatigue.

The increase in subjective fatigue before degradation of cognitive performance is a common finding for studies in the 'fatigue' paradigm (Holding, 1983). Certainly information processing performance is perhaps the most directly relevant variable when considering the overall capability of the man-machine

system. Momentary lapses of attention during a period of continuous performance have been cited as indications of fatigue. However these lapses tend to be of short duration and they do not always significantly affect an aggregated measure of performance (Stave, 1977). Lapses could be considered as changes in attention that are under voluntary control by subjects in an essentially self-paced task domain. In this sense the subject is exercising a form of choice, either conscious or unconscious in ongoing behaviour. Holding's review indicates that an area of human behaviour that is sensitive to fatigue involves tasks where risk and effort are variables in a choice of how and when to do the task.

The results of two pilot-fatigue experiments in the literature support these general propositions. Research on the effects of extended flying in a helicopter simulator indicated that a two-pilot team was able to maintain flying performance during sorties which occupied 14 hours per day with four hours scheduled sleep each night over five days (Krueger, Armstrong and Cisco, 1985). (The task of flying can generally be described as a psychomotor task based on the processing of information from aircraft instruments, and from other sources outside the cockpit.) The sorts of mistakes that did occur in the flying task were based on errors in judgement and the misreading of instruments. Errors included deviating from a well practised course, telling the air traffic controller they were at an intersection before they had reached it, and turning to intersect navigation bearing radial beacons too early or too late. Although these errors may have been due to lapses in attention, performance on flying assigned headings, altitudes, airspeeds and turn rates for hours and sometimes days was carried out within acceptable tolerances. Flight surgeons who examined the crews regularly indicated that most of the pilots were unsafe to fly on the evening of the third day but the pilots continued to fly well even into the fifth day. Stave's research (1977), also in a helicopter simulator, found that six or eight hours of flying did not show a gradual decline in performance as expected. Overall flying performance indicated a slight improvement over time. However there were short segments during the experiment which were marked by abnormally poor performance. The poor performance was attributed to lapses in attention which may have lasted for about 10 seconds. These lapses occurred at unpredictable times throughout the experiment.

These findings indicate that the most significant form of fatigue effect in aircrew may well be in terms of conscious or unconscious lapses in attention and in accepting greater risk options which involve less effort as fatigue increases. The better that operators are at information processing and psychomotor tasks then the lesser the performance degradation in these tasks due to fatigue and environmental stressors. Operating more capable aircraft which are less limited by weather and night conditions and which have multi-role flexibility may increase the hours that the aircraft are available for tasking. If there is not an adequate ratio of aircrew to aircraft then effective utilisation of the aircraft may be limited by aircrew fatigue issues. A further compounding factor is that the more flexible military systems tend to place greater emphasis on operator choice, in terms of tactical decision making, than their less flexible predecessors. Future research in this area should perhaps look at aspects of choice behaviour in respect of risk and effort variables in heat stress studies.

5.2 Additional Effects of Sleep Loss

A distinction has to be made between two 'fatigue' paradigms. In the first, the one considered in this report, it is assumed that a subject is well rested before the experiment and the duration of the experiment does not exceed a period when sleep loss could be considered a factor. The research data (Angus

and Heslegrave, 1985) indicate that performance decrements begin at about 18 hours without sleep, and in their study this coincided with the low point in the usual circadian body temperature cycle; that is around 5 am. The second fatigue paradigm is associated with total sleep loss for periods in excess of 24 hours. In this paradigm Angus and Heslegrave indicated that performance is maintained at the level it achieves at 18 hours of sleep loss until the next dip in the circadian body temperature cycle 24 hours later, when performance decreases further. In their study, over a 54 hour period without sleep, subjective feelings of fatigue increased over the first 18 hours and marked increases occurred at the same time as the performance decrements; that is at the low point of the circadian body temperature cycle.

The issue of subjective fatigue and its relation to performance is an interesting one as it may serve to help define a difference between fatigue due to a reduction in motivation, and fatigue due to sleep loss. Stave found that subjective fatigue increased over the time of the simulated helicopter sortie and that despite the length of the sortie, 3, 4 or 8 hours, the rating for fatigue reached the same maximum value at the end of the sortie, irrespective of the different durations. Stave, in his study where sleep loss was not a factor, concluded that subjective fatigue was conditioned by the pilots' perception of the time to go in the sortie, and that subjective fatigue was not related to objective work performance, but it was perhaps an indication of overall motiviation. In the sleep loss studies however, subjective fatigue and cognitive performance appear to show parallel effects over time. Therefore it appears feasible to conclude that a reliable reduction in cognitive performance will be associated with sleep loss and the circadian body temperature cycle, both of which are somewhat independent of motivation.

The effects of a hot environment on operator performance where sleep loss is a factor has, as far as these authors are aware, not been studied. However it is an important issue in operations that involve sustained periods of duty and where fractionated sleep schedules occur. The recuperative effects of naps and the interaction with hot thermal environments is an aspect of the Australian operations scenario worthy of further research.

6. RESUME

The high thermal loads on aircrew in the RAN's Sea King helicopters have been established previously, and various options for ameliorating the conditions have been proposed prior to this study. Engineering and financial reasons have prevented these options (eg air conditioning the whole cockpit and cabin space) from being implemented. This report contains a literature survey on the effects of heat stress on human performance (including a proposal for a heat stress index), an account of an experiment and a discussion

The literature survey indicates :

a. It is important for heat stressed aircrew to prevent or to try to prevent dehydration. To do this, aircrew should drink more fluid than would be the case under natural demand due to the sensation of thirst.

b. Body temperature is of central importance in heat stress studies but its measurement is difficult. It is desirable that the body temperature in heat stress experiments should be measured at two sites, viz the rectum and the external auditory meatus, adjacent to the tympanic membrane.

c. Skilled performance is affected by heat stress in a complex manner. Moderate heat stress may adversely affect the learning of tasks with a substantial cognitive component. Skilled operators tend to be less adversely affected by heat stress effects on performance than operators acquiring their skills.

d. Motivation may override many of the heat stress effects on human performance which have been demonstrated in laboratory studies.

Various options for preventing or ameliorating aircrew heat stress in the Sea King have been discussed. Liquid conditioned garments are currently not practicable because flightworthy systems are aparently not yet commercially available. Another option is simply to limit exposure to the hot conditions by using an index of thermal stress for the Sea King (SKITS), but this implies that there will be times when Sea King deployment will be limited by aircrew heat stress. A third option entails blowing cooled air at the faces of aircrew. This requires relatively small amounts of power in a vapour cycle system compared to the power in a system which is intended to provide cooling for the whole cockpit and cabin of the aircraft.

A controlled experiment was conducted in a thermal chamber to determine the effect of blowing cooled air at the faces of the RAN aircrew subjects. Measures of the effect were sought in physiological and biochemical variables, subjective rating scales and cognitive performance tasks. The results are :

a. Initially chosen temperature conditions in the thermal chamber had to be reduced in order for subjects to thermoregulare at or below 38.0°C Tcor. This was against expectations based on evidence from the research literature on the topic.

b. Aircrew who experienced blown cooled air had a significantly reduced sweat loss over a six hour exposure to relatively mild heat where the body temperature of the aircrew did not rise above 38.0°C.

c. Subjective ratings of thermal comfort, alertness and calmness decreased, and ratings of exhausted fatigue increased over time in relatively mild heat.

d. Skilled performance did not appear to be affected by fatigue factors of the degree experienced in the experiment.

e. Subjects were unanimously favourable in their reaction to the blown cooled air.

f. It appears likely that aircrew deep body temperatures will exceed 38.0°C in the Sea King aircraft on sorties lasting approximately six hours or more when the ambient ground level temperature is above 24.0°C.

In a section following the account of the experiment, evidence from the literature is cited which indicated that fatigue which is characterised by a change in subjective measures, when sleep loss is not a factor, will not necessarily be

related to a decrease in objective measures of information processing performance. However, increased fatigue may cause operators, when given a choice, to choose actions which involve more risk and less effort than would be the case when not fatigued. Evidence from the literature further indicated that operator information processing performance is affected by sleep loss. Modern aircraft are becoming increasingly independent of weather and daylight and tend to be available for more hours per day. If the aircrew/aircraft ratio is too small, aircraft utilization at the time of high demand for sorties will tend to be limited by aircrew fatigue; and heat stress effects may tend to make the limitations even more restrictive. It is suggested that the effects of hot thermal environments may exacerbate the effects of fatigue in situations where sleep loss or disrupted sleep patterns occur. Furthermore the recuperative effects of naps in hot environments is a worthy area for future research.

Operational trials will be required to demonstrate the practical feasibility, benefits and disadvantages of blown cool air from coaming- and helmet-mounted nozzles.

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This Report deals with thermal stress in aircrew operating in the cabin and cockpit environment of the RAN's Sea King helicopter. The high thermal loads experienced in the helicopter have previously been established and various options for ameliorating the conditions have also been proposed. A review of the literature on thermal stress research is presented. The development of an Index of Thermal Stress for the Sea King (SKITS) is reported along with the results of a study to determine the ameliorating effect of blown cooled air directed at the faces of subjects in a thermal chamber.

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